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13. ABSTRACT *(Maximum 200 words)*

This report describes the problems studied under the subject contract. Accomplishments are reported in force modeling, performance evaluation, and related supporting areas of optimization. Papers produced under the contract and scientific personnel participating in it are listed.

14. SUBJECT TERMS
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1. Problem studied

The primary aim of this research program was to investigate ways to help people to make better decisions about tradeoffs in resource allocation, in situations frequently involving uncertainty, with particular application to Army problems in force mix and weapon mix issues.

One of the main areas was the computational implementation of large scale scenario analysis models. Such models employ a finite probability distribution describing different *scenarios* (that is, possible states of the decision environment), and they then compute solutions that optimize against these scenarios according to some appropriate decision criterion. For example, one might seek a decision that provided maximum expected performance on some measure of effectiveness, subject to various operational constraints (which can be different in different scenarios), or one might look for a decision providing minimum variance in performance across scenarios, subject to a floor on expected performance.

Scenario analysis models of relatively modest size can be built and run as units: that is, they result in optimization models that can be run in current computers without special procedures. On the other hand, if the number of scenarios becomes large, if many systems must be considered, and/or if relatively fine detail in the modeling of each scenario is required, then the resulting optimization models are likely to be too large to fit in the memory of the computer being used. In that case the model has to be broken up into separate pieces, and the pieces have to be subjected to an iterative procedure involving separate solution of each piece, followed by modification of the pieces using the solution results, and subsequent re-solution. The general name for such procedures is *decomposition.*

Decomposition methods have been known for about 30 years, but the early methods tended to be quite slow, and they did not always work well. Recently several new ideas have been proposed for decomposition, which lead to classes of methods considerably faster than the older techniques. We investigated one of the most promising of these techniques, the so-called bundle class of methods, to determine whether it would work well in dealing with scenario analysis problems.

In addition to work on the bundle method, we developed various other techniques to contribute to quantitative assessment of force performance. We also carried on collateral research in the underlying field of nonsmooth optimization, which contributes to both of the areas already mentioned.

2. Principal results achieved

The main practical result achieved from this work was computational implementation of the so-called bundle-trust region (BTR) method, and its testing on numerous scenario analysis problems, including force mix problems furnished by the U.S. Army TRADOC Analysis Command (TRAC).

We found that for these problems it provides a very much faster solution method than the best current method (the progressive hedging algorithm of Rockafellar and Wets). The implementation portion of this work is described in the technical report of Chun *et al.* described in Section 3, and selected test results are presented in the doctoral dissertation of B.J. Chun, also listed in Section 3. Work is currently going forward to prepare these results for scientific journal publication.

We also began investigating the feasibility of using scenario analysis formulations to support valuation of uncertain information (for example, from testing of a system) through the use of Bayesian analysis. Essentially, one uses the scenario analysis model as a substitute for an assessed utility function. This is a new area, and it will require considerable work before we can see whether it is likely to pay off substantially in real decisions.

In another part of the work, also aimed at improving tools for effective combat modeling in support of decision making, two draft papers on shadow pricing were revised (these are listed in Section 3). The revised papers have been accepted by *Operations Research*. In the first of them, we showed how to extend the classical eigenvalue weights (linear weights) so that the model could handle systems fighting in groups, as they do in actual combat, and we showed that the extended model permitted positive values for non-killing systems. This eliminated a well known problem with the eigenvalue weights, which do not permit positive values for any non-killing systems, even though the latter might be essential (for example, trucks).

We also showed that the eigenvalue weights are actually shadow prices of a certain optimization model, and that therefore they rigorously measure instantaneous tradeoffs in force survivability. This was a fact that had not been previously known, and which in fact had been conjectured to be untrue. Finally, we showed how to compute a solution to the extended model by iterative linear programming, in time proportional to $-\log \epsilon$, where ϵ is the required accuracy.

The second of these two papers showed how to extend the linear model to cases in which the functions entering into the model contained significant nonlinearities. We were able to prove that a solution would exist under reasonable hypotheses, but at this time no effective computational method is known.

We also applied a technique similar to that used in the papers just described, to show how to make cost/benefit analysis comparisons of a portfolio of projects or systems having performance measures on distinct, incommensurable attributes. This work is described in the paper, "Minimax cost/benefit analysis," listed in Section 3.

In other work supported in part by this contract, we investigated so-called *normal maps*, which are devices for converting variational inequalities into single-valued, although generally nonsmooth, equations. Zeros of the equations correspond one-to-one with solutions of the variational problems. Further, many of the methods of the differential calculus can be carried over to these problems *even though the functions involved are nonsmooth*, if the methods are suitably adapted. We studied the extension of such calculus methods, and the additional knowledge that can be gained about the variational problems through exploitation of this approach. Recent papers in this area are listed in Section 3.

3. Publications and technical reports

The following papers acknowledge support from Contract DAAL03-89-K-0149:

B. J. Chun, *Scenario Analysis Modeling and Decomposition Methods for Optimization Under Uncertainty*. Dissertation submitted in partial fulfillment of the requirements for the degree of Doctor of Philosophy (Industrial Engineering) at the University of Wisconsin–Madison, 1992.

B. J. Chun, S. Lee, and S. M. Robinson, "An implementation of the bundle decomposition algorithm," *Technical Report No. 91-6*, Department of Industrial Engineering, University of Wisconsin–Madison, Madison, WI, 1991.

S. M. Robinson, "Shadow prices for measures of effectiveness, I: Linear model," accepted by *Operations Research*.

S. M. Robinson, "Shadow prices for measures of effectiveness, II: General model," accepted by *Operations Research*.

S. M. Robinson, "Homeomorphism conditions for normal maps of polyhedra," in: A Ioffe, M. Marcus, and S. Reich (eds.), *Optimization and Nonlinear Analysis*, Longman (Pitman Research Notes in Mathematics Series No. 244), Harlow, Essex, England 1992, pp. 240–248.

S. M. Robinson, "Normal maps induced by linear transformations," *Mathematics of Operations Research* **17** (1992), pp. 691–714.

S. M. Robinson, "Nonsingularity and symmetry for linear normal maps," accepted by *Mathematical Programming*.

S. M. Robinson, "Minimax cost/benefit analysis," submitted to *Management Science*.

S. M. Robinson, "Scenario analysis: What it is and how it works," informal expository paper prepared for Army analysts and other users.

4. Participating scientific personnel

The following scientific personnel participated in the work under Contract DAAL03-89-K-0149 during part or all of its duration.

Stephen M. Robinson, Professor.

Ju-Long Chen, Research Assistant.

Bock Jin Chun, Research Assistant (received degree of Doctor of Philosophy).

Sangjin Lee, Research Assistant.

Byung Ho Min, Research Assistant (received degree of Master of Science, Industrial Engineering)

Santanu Pal, Research Assistant (received degree of Master of Science, Industrial Engineering).

Sheng-Yuan Shen, Research Assistant.

5. Reportable inventions

To the best of the principal investigator's knowledge, there were no reportable inventions during the course of this research.